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THESIS

**TIME DEPENDENT BEHAVIOR OF LIGHT EMITTING
POLYMERS FOR POTENTIAL INDIVIDUAL IDENTIFY
FRIEND OR FOE (IFF) APPLICATIONS**

by

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December 2007

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**TIME DEPENDENT BEHAVIOR OF LIGHT EMITTING POLYMERS FOR
POTENTIAL INDIVIDUAL IDENTIFY FRIEND OR FOE (IIFF)
APPLICATIONS**

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Light Emitting Polymers (LEPs) are being developed for lightweight, low cost, infrared emitters for potential Individual IFF applications. The unique requirements for emitter operation (modulated, short term response) require study of time dependent optical and electrical behavior. Multiple LEP devices were evaluated to determine intensity variations and voltage response as a function of time and activations. From experimental data, it became possible to suggest approaches for creating the optimum LEP device for future IIFF devices.

Key results included the increase of intensity in all emitters, observation of necessary ‘warm-up’ periods for yellow devices, large voltage responses of red emitters, and device ‘reset’ time. All emitters saw intensity increase while being activated continuously over short periods of time. The yellow emitter had the largest intensity variation, so a ‘warm-up’ period of constant current was used, significantly impacting the intensity. The red devices were determined to have large turn-on voltages at initial activation. The device ‘reset’ time, or the time for the intensity to drop after reaching optimum intensity was also determined.

Further research into the combination of red and yellow dyes is suggested, as well as continued research into the impact that small periods of operating time have on LEP intensity.

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I. INTRODUCTION

A. MILITARY FRATRICIDE

“Fratricide is the employment of friendly weapons and munitions with the intent to kill the enemy or destroy his equipment, or facilities, which results in unforeseen and unintentional death or injury to friendly personnel [1].” Military fratricide, or friendly fire, occurs because uncertainty, miscommunication, and human error are always present on a battlefield. This is truer today than it has been for centuries, even with the advanced technology that our military forces utilize. The Gulf War saw only 147 combat deaths, but 35 of those (24%) were killed by friendly fire [2]. In comparison the data from World War II and Vietnam show that only 3% of casualties were attributed to friendly fire [2]. The increasingly complex, undefined battle space, made possible by precision weapons and advanced sensors, creates a dangerous battle field for the individual soldier.

Over confidence in the precision of weapons, the assumed accuracy of sensor systems and the shortened time for decision making has actually increased the chances for friendly fire incidents to occur, especially in limited visibility situations (night, fog, dust storms, etc.) where sensors must be relied on. Those same precision weapons and advanced sensors have reduced the number of casualties, while increasing the probability that those casualties will be friendly soldiers. The consequences of such fratricide have also increased, as the American public demands an accounting for each military life lost in combat. There is a great need to provide an effective means of rapid, reliable identification for individual soldiers in order to prevent military fratricide incidents.

B. INDIVIDUAL IDENTIFY FRIEND OR FOE

Large items such as aircraft have systems designed to prevent friendly fire incidents. These systems are commonly grouped under the common name Identify Friend or Foe (IFF). These systems rely on radio transmissions, codes and large pieces of

hardware to provide location and unit information about each individual aircraft [3]. Efforts to develop a similar system for the individual ground soldier, an Individual IFF (IIFF), have been spotty and hampered by several realities.

The first reality is that an infantry soldier already carries more weight than he should. The average weight of a soldier's pack, depending on the type of march being performed, is between 63-127 lbs, when the Army field manual calls for 48-150 lbs [4]. Any IIFF device must not add to the weight already too heavy to bear. Two of the current IIFF devices in use by U.S. forces in Iraq and Afghanistan illustrate this criterion: an infra-red (IR) reflective patch with a design of an American flag (Figure 1) has a Velcro™ backing so that it can be worn attached to sleeves, rucksacks, and helmets, and a small hand-held emitter that emits IR light in pulses, the Phoenix Light [3].

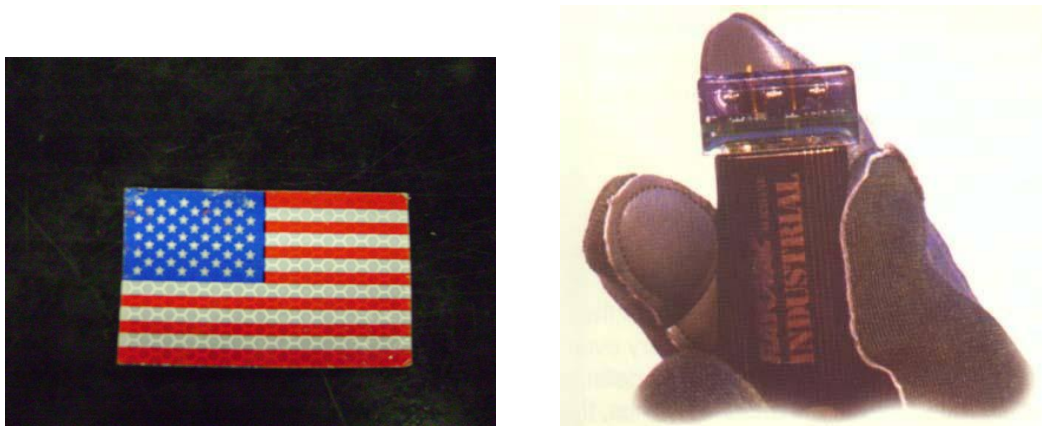


Figure 1. IR IIFF Flag and Phoenix Light (From: [5])

The second reality is that no soldier wants to wear a device that advertises his position to the enemy, so the device ideally must be 'smart.' A 'smart' device is one that only responds to a friendly interrogator, either because the interrogator has the right code or the right frequency. In this way, enemy forces are unable to use the IIFF to locate U.S. troops. Unfortunately, the IR IIFF Flag is not 'smart,' because it reflects any IR source, and the Phoenix Light is not 'smart' because it is a continual emitter. Efforts to make 'smart' device have run into the third reality, affordability.

Unlike a million dollar airplane, the ground soldier is more exposed to the elements and wear and tear of battle. As such, his equipment is subject to bumps, weather conditions (dust, rain, cold, heat), and enemy action. In addition, there are many more ground soldiers than there are tanks and aircraft, so that many more identifiers are required. Any IIFF device that a soldier wears must be durable, and easily replaceable, a consumable item. A consumable item is an item in the supply chain that is easy to get, affordable, and expected to need replacement often.

Understanding these limitations, a collaboration began in 2005 between Add-Vision, Inc. (AVI), Scotts Valley, CA, and the Naval Postgraduate School, which has resulted in the creation of an individual identify friend-or-foe (IIFF) patch that is lightweight, ‘smart,’ and affordable. Originally designed by a SEAL, the IIFF patch offers a solution to reducing the risk of military fratricide for ground troops.

C. IIFF PATCH ADVANTAGES

The patch (Figure 2) combines a unique triggering approach with a novel patented approach of producing Polymer-Organic Light Emitting Displays (p-OLEDs), which makes it flexible and lightweight. It only weighs 79 g, uses a 1.5 V replaceable AAA battery, with dimensions of 11.5 cm x 8.5 cm. Like the IR IIFF Flag, the IIFF patch uses Velcro™ to attach to the uniform, rucksack or helmet of a soldier. In prototype form, the device has been shown to operate in a temperature range of -40 - 71 ° C and after immersion in shallow water for up to an hour [6].



Figure 2. IIFF Patch Generation 3

Unlike a reflective IIFF Flag, the PLED IIFF Patch is also ‘smart.’ It contains a photodiode that is used to trigger the emitter response. The device only responds when activated by a targeting laser that is modulated at a designated frequency. Targeting lasers, such as the ATPIAL laser (Figure 3), are already in use by American ground forces, and therefore there would be no need for major changes in current operating procedures. Upon being illuminated by the targeting laser, the IIFF patch emits 5 pulses of light in 1.2 seconds in the near-IR range. The broadband emission which will be described in Chapter II is filtered so that all visible light is removed and only an IR signal remains. This emission is in the specific range that night vision goggles (NVGs) already in use by U.S. forces utilize. The current IIFF patch also has a second mode, a ‘beacon’ mode. The device can be switched on to ‘beacon’ mode and it will pulse continuously until turned off, again only emitting infrared light.



Figure 3. ATPIAL Laser

The IIFF patch is also affordable, thanks to Add-Vision, Inc.’s patented screen printing technique. Screen printing, which will be discussed later in this thesis, is a cost-reducing and fast method because it does not require specialized equipment to enable the production of the device [7]. While no large scale production of the IIFF patch has yet been attempted, the estimated cost per patch for large quantities is ~\$20, which places it easily in the consumable range.

D. IIFF PATCH UNKNOWNNS

For all the potential advantages of the IIFF patch, there are some outstanding questions that have not been addressed, including life expectancy and electrical and optical transient behavior. Unlike the commercial products that are the focus of AVI's core business, the pulsed emission of the IIFF and its operational usage pattern (critical, but rare activation) place unique demands on the product.

AVI's data suggested that the Light Emitting Polymer (LEP) layer of the patch would maintain its intensity for months; however, all their research was focused on the behavior of the p-OLED as a display device, meaning the device was turned on and brightness measurements were not made for D.C. conditions for thousands of hours of operation. Specific studies had not been performed on the immediate turn-on behavior of the LEP, specifically intensity and voltage variations in the first few seconds of activation.

The IIFF patch would have a completely different usage pattern than that of Add-Vision's commercial products. The device would be turned on at dusk or before a unit went on patrol, and would then be left in 'detect' mode for large periods of time. The device would only activate if interrogated by a friendly targeting laser, and it is entirely feasible that the device could be on for 10-12 hours and never be activated. The device would then be turned off at dawn or the return of the unit to a secure camp, and then left exposed to the environment for any period of time (next patrol, next night, next mission, etc...). There were no data to suggest how this usage pattern would affect the intensity and the lifetime of the LEP.

Research conducted by Captain Patrick Williams, USMC on the transient behavior of the IIFF patch demonstrated that the emitter intensity decreased with short usage times intermittent with long inactive periods, as illustrated in Figure 2 [6]. The patch was tested five days a week. Each time the device was activated five times to achieve optimum intensity, and the average intensity of the left and right side of the chevron (integrated over one activation or 5 pulses) was captured during the fifth activation [6].

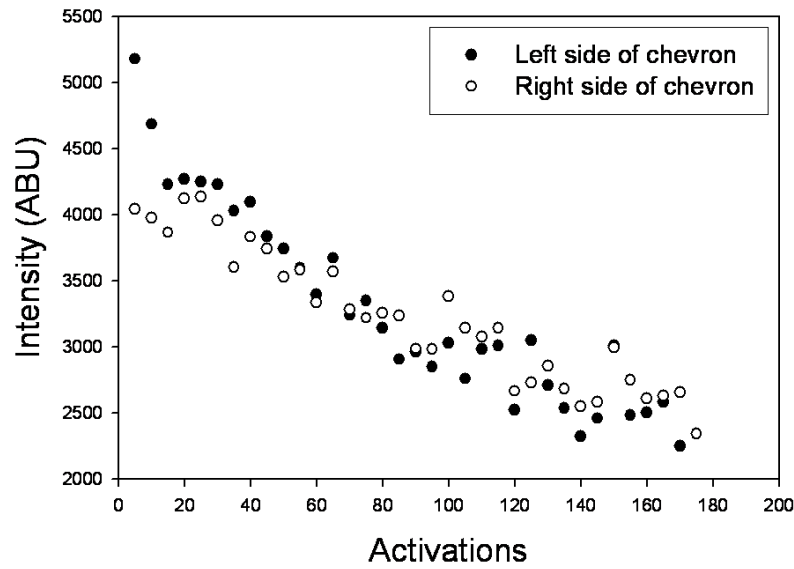


Figure 4. G3 IIFF Patch, Intensity as a Function of Activations, Over Total Period of 68 Days (After: [6])

However, it was also shown that intensity would increase (Figure 5) if the patch was activated repeatedly in a short amount of time. In this case, the patch was activated 21 times (five pulses per activation) in a period of 5 minutes. Each time the average intensity of the left and right side of the chevron was captured [6].

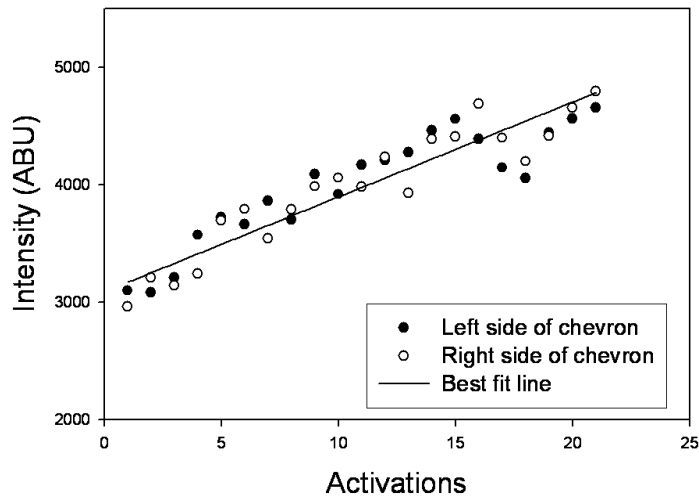


Figure 5. G3 IIFF Patch, Intensity as a function of Activations, Over Total Time of 5 minutes (After: [6])

These data indicated that there were multiple timescales of interest to the operation of the IIFF patch: the lifetime of the patch (or how many days it would last), the time to reach maximum intensity (or how many hours it could maintain maximum intensity), and the short term voltage requirements (or how much voltage was required to activate the device in the first second). The lifetime of the patch will be a function of the battery and p-OLED encapsulation, so by taking the battery out of the equation by providing a steady source of current, the encapsulation methods can be tested and compared to find the one that promotes the longest lifetime. The maximum intensity is affected by the LEP inside the p-OLED, how efficiently it combines electrons and holes, so by testing several different LEP types the one device that provides optimum intensity for the longest period of time can be found. The voltage turn-on is also affected by the LEP inside the p-OLED, so by testing different LEPs, the one that requires the least voltage for turn on can be determined.

The goal of this work was to explore the various relationships between driving current, response voltage and intensity over the multiple timescales of interest (days, hours and seconds). The relationship between short term activations and long term storage, the role of multiple activations on the intensity and the voltage response, and the effect that voltage response would have on the intensity all needed to be investigated in order to provide data on which type of LEP provided the optimum intensity, lifetime and voltage response for the p-OLED that will be used to make the IIFF patch.

E. THESIS OVERVIEW

Chapter I provides a background on the development of the IIFF patch, the various questions concerning lifetime and intensity of the p-OLED, and the goals of this thesis. Chapter II addresses how p-OLEDs are made, LEP behavior, how Light Emitting Electro-chemical Cells (LECs) can be used to approximate the behavior of LEPs, and the expected behavior from the IIFF patch LEPs. Chapter III describes the equipment used to perform the experiments, the methodology, and a detailed list of the individual experiments completed. Chapter IV presents and describes the experimental results. Chapter V summarizes the conclusion and discusses areas of future research.

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II. BEHAVIOR OF LIGHT EMITTING POLYMERS

A. CONVENTIONAL P-OLED DESIGN

P-OLEDs, as shown in Figure 6, were first reported by Burroughes et al. in 1990 [8]. The Aluminum and Indium Tin Oxide (ITO) layers act as the anode and cathode. When voltage is applied across the p-OLED the electrons and holes recombine to emit light, the wavelength of the light being determined by the light emitting polymer (LEP) [9]. The p-OLEDs utilize a driving current on the order of milliamps, while the resulting voltage is determined by the device structure. P-OLEDs are useful for thin lighting displays that operate under low voltages, such as watches, cell phone screens, and signs [7].

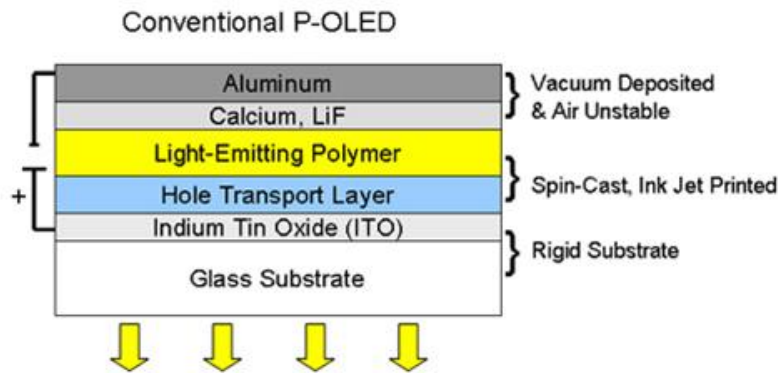


Figure 6. Conventional p-OLED (From: [7])

The original method of construction of p-OLEDs was physical vapor deposition [10]. Today, conventional p-OLEDs are spin cast or printed via ink jet on a glass substrate [7]. Spin coating is limited because it does not allow the various layers to vary from the shape of the device, limiting the design [9]. Ink jet printing is also limited since the ink can splash or smear in the printing process, thus affecting the resolution of the device [11]. The major shortcoming of conventional p-OLEDs is cost, due to the fact that the cathode is not air stable, and so requires expensive vacuum equipment to produce [12]. Other shortcomings include the lack of flexibility due to the glass substrate, and the susceptibility to degradation due to moisture [12].

B. ADD-VISION, INC. P-OLED

AVI's p-OLEDs, such as the IIFF Patch, are made up of only four layers, a transparent flexible substrate, an ITO anode, a LEP, and a Silver cathode (Figure 7). The ITO, the LEP and the silver cathode are screen printed onto the substrate, a process that is done under atmospheric conditions [13]. The printed electrode layer can include additives to improve charge injection and LEP performance [14]. An encapsulation process seals the p-OLED from oxygen and water in order to extend LEP life and prevent degradation of the device [12]. The final product is a p-OLED that has low-voltage operation, uniform emission, and high efficiency [7].

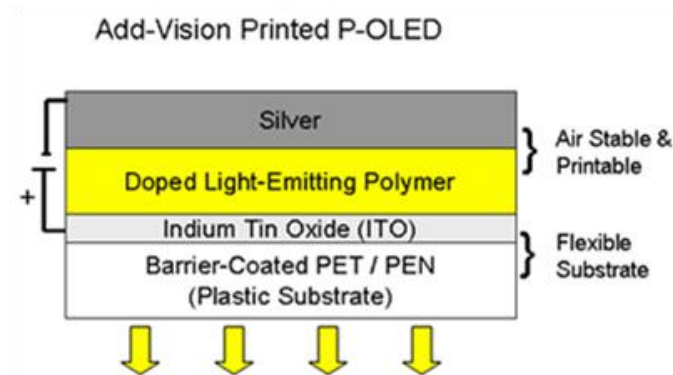


Figure 7. Add-Vision, Inc. Screen Printed P-OLED (From: [7])

Screen printing p-OLEDs is important for several reasons: cost, design, and speed. An air stable cathode that can be screen printed onto the device means that no expensive equipment to maintain a vacuum is required [13]. Screen printing reduces the cost of production, while allowing the manufacturer to design almost any emitter pattern for a p-OLED [10]. The speed of production is also increased since screen printing uses air stable elements [7]. Screen-printing is also considered to be environmentally-friendly [11].

C. LIGHT EMITTING POLYMERS

LEPs have semiconducting electrical properties while maintaining a typical polymer convenience. The LEP is printed using an electroluminescent polymer ink which has additives and dopants to improve ink viscosity, ink consistency, charge

injection, and power efficiency [14]. The ink can also be mixed with luminescent dyes in order to change the frequency of the light emitted. Inside the LEP, the mobile dopant species move under an applied field, which causes changes in the electron or hole injection balance. As a result, time dependent behaviors are more problematic than with inorganic semiconductors. Issues of long term stability are important in the commercialization of these materials.

The IIFF Generation 3 patches use a yellow LEP, which has an emission tail in the infra-red (IR) emission from 700 to 900 nm. A red dye for use in the LEP was developed with the goal of emitting more light in the near-IR range than the yellow LEPs, which would increase the efficiency of the IIFF device. The relative emission intensities were measured by using an Oxford Instrument 0.3 m grating spectrometer with a parabolic mirror collector and a GaAs photomultiplier tube detector. The results are displayed in Figure 8. The yellow sample had an over-all greater intensity, but the red sample had greater intensity in the region of interest.

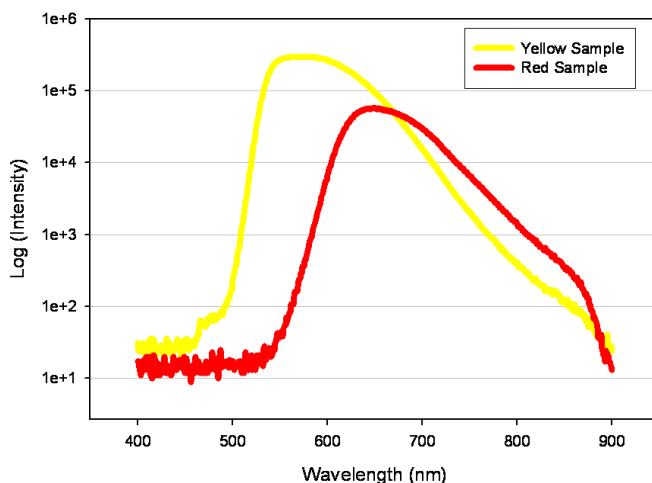


Figure 8. Log(Intensity) as a Function of Wavelength, Yellow vs. Red Emitters

D. LIGHT EMITTING ELECTROCHEMICAL CELLS

A close relative of LEPs are the frozen-junction light-emitting electrochemical cells (LECs) [15]. A LEC has a polymer layered between metal electrodes, so that when

voltage is applied, the polymer is reversed doped to create n type and p type regions [16]. A frozen-junction LEC is a LEC that has been cooled to ~200 K while fully-turned on, so that the ions are frozen in place [17]. LECs emit light when voltage is applied to the polymer and a p-n or p-i-n junction forms which causes electron and hole recombination and light emission within the junction [16]. LECs are manufactured by spin coating or ink jet printing, and like LEPs, the wavelength of light emitted depends on the energy gap of the polymer [16]. Like LEPs, LECs are vulnerable to humidity and overdriving voltages, which can cause degradation of the devices [17]. Other similarities include the low current and small turn-on voltage required [16].

Unlike LEPs, the LEC components are air stable during manufacture, so the advantage of screen printing is muted [16]. However, only a frozen-junction LEC is comparable to an LEP, so there is associated cost with cooling the LEC down, and keeping it cooled down during operation. LECs also have a slower turn on time, since the p-n/p-i-n junction must be formed upon voltage being applied [18]. Another shortcoming of LECs is the possibility of the emission zone not being centered on the device, since the p-n junction can form anywhere in the polymer [18].

E. LEC INTENSITY FLUX

LECs have been observed to show variations in luminescent efficiency and increased voltage over time [15, 17]. One theory is that under a constant current the electron mobility is reduced, which increases the probability of electron-hole recombination [15]. The reduction in electron mobility narrows the emission zone, which makes the device more efficient, and thus increases intensity [15]. The change in intensity for LECs has also been attributed the ability of the substrate, under constant current, to dissipate heat which effects the operating temperature of the device which then promotes p-n junction relaxation which results in doping relaxation [17].

This time-dependent increase in intensity of LECs is of particular interest in light of William's data cited in Chapter I. If LECs are similar to LEPs, than the behavior matches what has been seen in LEPs, and therefore the explanation may be the same. However, LEC research has been focused on devices driven by a d.c. current, whereas the

IIFF device and associated LEPs are driven with a pulsed current. The luminescent variations predicted by the behavior of LECs may not appear in pulsed LEPs or may point to a design change required for optimum performance of the IIFF patch. The experimental work in the next section was designed to address these questions.

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III. EXPERIMENTAL SETUP

A. DESCRIPTION OF EQUIPMENT

In order to more completely understand the relevant transient behavior of the LEP devices, the devices had to be electrically driven in a similar manner as the ones in the IIFF patch. The objective was to measure the device voltage and intensity of emission during a series of activation cycles. Add-Vision, Inc., in Scotts Valley, CA, provided the LEP structures listed in Table 1. Encapsulation refers to the layer between the OLED and the adhesive; “standard” refers to a buffer layer, while “getter” indicates an improved desiccant layer. The “new top” cathode refers to a polymer binder and solvent system which contributes to lower voltage climb and a longer lifetime; “old top” cathode refers to the binder and solvent system that is found in the IIFF.

Quantity	Color	Encapsulation	Cathode	Sample
2	Yellow	Standard	New Top	A
4	Yellow	Getter	New Top	B
2	Yellow	Standard	Old Top	C
2	Red	Getter	New Top	D

Table 1. LEP Structures Provided by Add-Vision, Inc.

Figure 9 shows a yellow LEP test device and a red LEP test device. Every device is $2 \times 1 \text{ cm}^2$, with 2 pixels per device. The devices are mounted in 1.25 mm FFC/FPC R/A connectors so that they can be biased. Both pixels share the same cathode, but each pixel has its own anode.

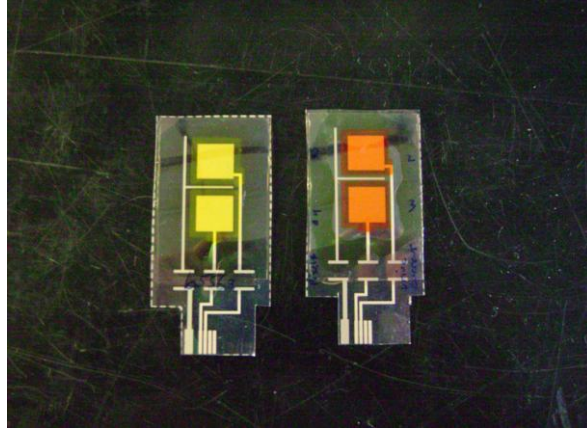


Figure 9. Yellow LEP and Red LEP P-OLED Devices

A Keithley 2400 Source Meter was used to source current by pulsing five times in a period of 1.2 seconds, creating five pulses of 120 ms duration. A basic source-measure operation was performed using a 2-wire local sense connection. (The resistance of the devices is on the order of several thousand amps, so there is no concern for a possible resistance drop across the leads). In order provide a pulsed driving current output; the source meter had to be programmed externally. This was done by using the software program HyperTerminal, a baud rate of 9600, and a RS-232 cable. This allowed for remote programming and initiation of the source meter. In order to program the pulses via the source meter, the source meter parameters (Table 2) and the established parameters (Table 3) had to be used to calculate A/D Conversion (A/D), Source Delay (S_D), and Trigger Delay (T_D).

Number of Power Lines Cycle (NPLC)	0.08
Power Life Frequency (f_{pl})	60
Trigger Latency (T_L)	225 μ s
Source Configuration (S_c)	50 μ s

Table 2. Keithley 2400 Source Meter Parameters (From: [19])

Trigger Count	5
Voltage Compliance	60 V
Source on Time (T_{on})	120 ms
Source off Time (T_{off})	120 ms
Source Current	3 mA

Table 3. Established Pulse Requirements

A/D was calculated as $185 \mu s$ using the following equation:

$$A/D = [NPLC * \frac{1}{f_{pl}}] + 185 \mu s \quad (1)$$

S_D and T_D were then calculated to be 0.118432 seconds and 0.11978 seconds using the following relationships, which were established using Figure 10.

$$T_{on} = S_c + S_D + A/D \quad (2)$$

$$T_{off} = T_L + T_D \quad (3)$$

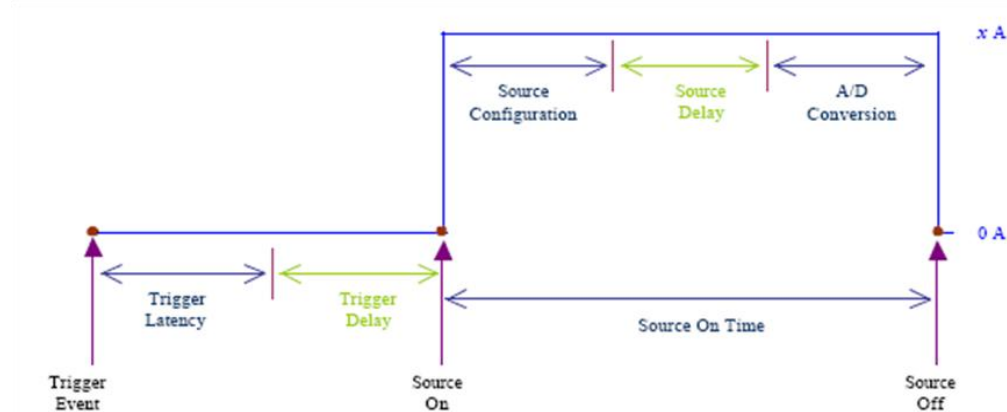


Figure 10. Keithley 2400 Source Meter Pulse Setup (From: [19])

To capture the voltage response and the intensity, an oscilloscope and a CCD camera were used. A Tektronix TDS 3032B Oscilloscope was set at 10 V/division on the y-axis and 200 ms/division on the x-axis, with the trigger set to capture all 5 pulses. The resulting data points were then saved to a disk and transferred to the CPU for analysis.

An Apogee CCD Camera, Model KX1E, was used to take an image of the flashing device using a total exposure time of 5 seconds and a 768 x 512 pixel² array. The software program MaxIm DL Version 3.10 was then used to analyze the images for intensity values.

Each device was placed in an R/A connector, with wires soldered to the connections. The devices were then mounted with Velcro™ to the side of a rectangular box (3'x1'x1'), facing the CCD camera from a distance of 1.5 ft. The camera was fixed in a frame to prevent the optics from shifting. The wires were attached via leads to the oscilloscope and the source meter. The interior of the box was painted flat black to prevent reflection and the top of the box was closed to prevent ambient light from entering.

While there were several types of experiments performed, the procedures were very similar. The camera was cooled to a set point of -10° C, the source meter was programmed with the required set points, and the oscilloscope set points were established. The expose button for the camera was activated, the source meter received its activation code, and data were acquired for 5 sec by the various devices. Figure 11 shows a schematic overview of the input current cycle and the matching image acquisition time. The data were then transferred to a file on the CPU and the entire process was repeated. There were several times when a constant current of 3 mA was required. This was achieved by locally programming the source meter for 3 mA and 60 V compliance, and then using the CPU clock to time the process.

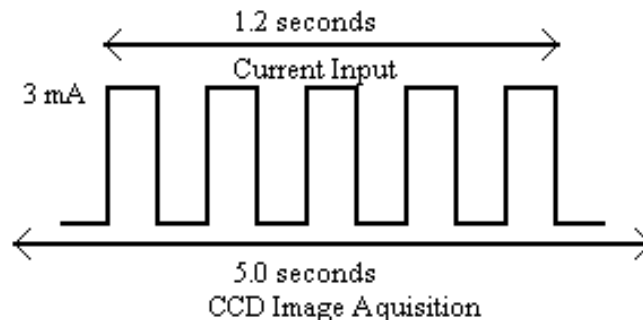


Figure 11. Data Acquisition Timescale Graphic

The experiment involving emission measurements from the actual IIFF patch used the following procedure: the patch was placed in front of the CCD camera and activated with the laser. The patch was then placed in beacon mode (patch pulses continuously) for five minutes, then turned off and then back on. Finally, the patch was activated once more, and the resulting image captured.

It was also important when analyzing the intensity images, that the same size data box was used in each case, since the size of the box impacted the average intensity values. MaxIm DL displayed the full image, of which the emission area of the device was only a small fraction. Using the crop tool, the images were reduced to an array of 88 x 80 pixels² in order to incorporate as little of the background as possible. Then a crop box of the same dimensions was used to create a background image. Since each image was cropped to the exact same size, comparison of average intensity was allowed between multiple devices. The corrected intensity value was established by subtracting the intensity of the background image from the image. The corrected intensity values were then normalized to provide a fractional representation of intensity change. All of these values were then plotted, along with the voltage data, using the software program SigmaPlot 9.01.

B. EXPERIMENTAL PROCEDURES

A variety of questions needed to be addressed to compare overall performances of Yellow and Red emitters. How were voltage requirements affected by time? How was intensity affected by time? What timescale provided the best voltage usage and brightest intensity levels? Which was brighter, yellow or red? Which had the highest resistivity, requiring the largest turn-on voltage, red or yellow? In order to answer these questions, the following experiments were accomplished:

- Experiment One: Compare three types of yellow emitters (A/B/C), activating them every other day. Capture intensity and voltage data and determine the optimum yellow sample. This is similar to the experiment previously performed with the IIFF patch. (Pulse each sample at 3 mA 5 times in 1.2 seconds every 48 hours for 52 days).

- Experiment Two: Compare a yellow sample's continuous activation over a shorter timeframe versus the limited activations of Experiment One. Capture intensity and voltage data, and determine effect on intensity. This is similar to previous experiment measuring continuous activation of the IIFF patch. (Pulse Sample A at 3 mA 5 times in 1.2 seconds every 5 min for 5 hours).
- Experiment Three: Compare voltage and intensity changes between a yellow sample with no warm-up and one with a ten minute warm-up. Capture intensity and voltage data, and determine which method provides the best intensity. (Pulse Sample B at 3 mA 5 times in 1.2 seconds, then provide a steady current of 3 mA for 10 min, then pulse sample 5 times in 1.2 seconds every 5 min for 3 hours).
- Experiment Four: Establish a baseline set of data for a red sample for comparison against yellow data from Experiment One. Capture intensity and voltage data, and determine which has the optimum intensity. (Pulse Sample D at 3 mA 5 times in 1.2 seconds every 5 minutes for 3 hours).
- Experiment Five: Using a red sample, compare the intensity and voltage for sample warmed-up for 10 min versus the sample without a warm-up. (Pulse Sample D at 3 mA 5 times in 1.2 seconds, then provide a steady current of 3 mA for 10 minutes, then pulse the sample 5 times in 1.2 seconds every 5 minutes for 3 hours).
- Experiment Six: Establish how long the intensity of a red sample remains at the optimum level. (Experiment 6a: Pulse Sample D at 3 mA 5 times in 1.2 sec, then provide a steady current of 3 mA for 10 min, then pulse the sample 5 times in 1.2 seconds every 30 min for 210 minutes). (Experiment 6b: Pulse Sample D at 3 mA 5 times in 1.2 sec, then provide a steady current of 3 mA for 10 min, then pulse the sample 5 times in 1.2 sec every 24 hours for 4 days).
- Experiment Seven: Compare a current IIFF Generation 3 patch's intensity after a 5 min warm-up to its intensity with no warm-up. (Turn on patch, activate with laser. Turn off patch and then turn on in beacon mode (continuous flashing) for 5 min. Turn off patch, turn back on and activate with laser).

IV. RESULTS

A. INITIAL YELLOW DEVICES

Using a series of yellow emitters, three experiments were performed. The first used three samples, the standard encapsulation with new top cathode (A), the getter encapsulation with new top cathode (B) and the standard encapsulation with old top cathode (C). The second experiment used the standard encapsulation device with new top cathode (A). The third experiment used the getter encapsulation with new top cathode (B). For all three experiments, intensity and voltage response data under pulsed current bias were collected and analyzed.

1. Intensity

The normalized intensity of the three yellow samples showed similar trends while reflecting the individual differences between the samples. Since sample B was the most advanced device, its intensity had the least fractional change (23 %), followed by Sample A (35 %) and finally, Sample C (53 %). The sampled intensity of the three emitters decayed over time as expected, as shown in Figure 12. Continued exposure to moisture in the ambient air is believed to play a role in this intensity decrease over extended periods of time.

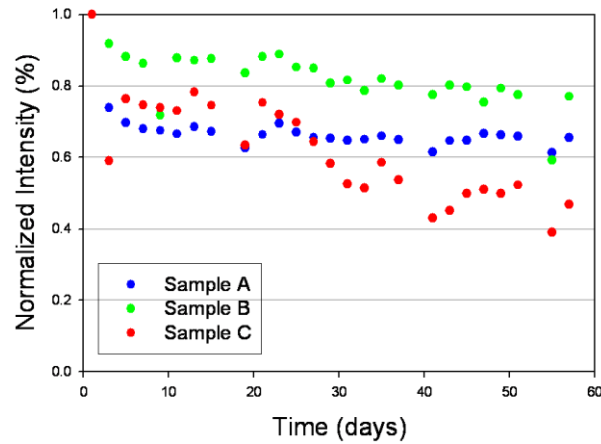


Figure 12. Experiment One: Normalized Intensity as a Function of Time, Activation Every 48 hours

Previous work had suggested that the intensity would actually increase as the device was repeatedly pulsed over a shorter period of time. The shorter time frame between pulses would eliminate long term effects from humidity, while probing transient effects of current bias on intensity of emission. Experiment Two pulsed Sample A over a relatively short period of time (5 hours) to measure variations in intensity. The results, shown in Figure 13, confirmed the trend previously reported. The intensity increased by ~ 80 % as the sample was pulsed over the 250 minute duration.

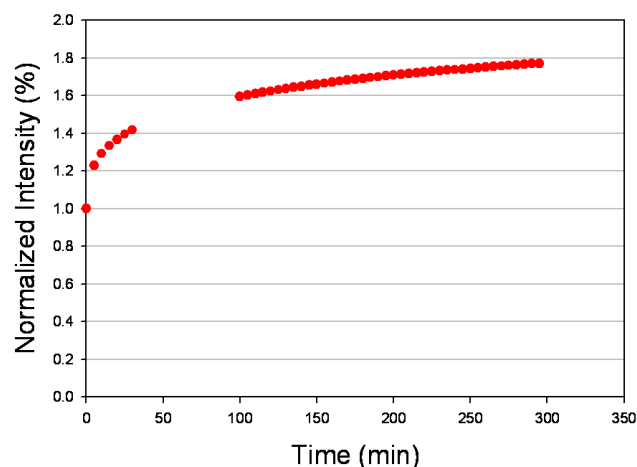


Figure 13. Experiment Two: Sample A Normalized Intensity as a Function of Time, Activation Every 5 minutes

The results of the second experiment suggested that the devices were not at maximum intensity when initially activated, and that a “warm-up” period was required before the devices could achieve their optimum intensity. Experiment Three used a warm-up period of 10 minutes at a steady current of 3 mA. (Warm-up time was selected as 10 minutes as a reasonable, but arbitrary period that could be feasible in actual device operation). Sample B, as the optimum sample from Experiment One, was used.

The results in Figure 14 do demonstrate that a warm-up period is an effective way to get the sample to achieve a much greater intensity from the emitter. The change in intensity was so dramatic that any IIFF patch design using current materials should include a warm-up period of some duration.

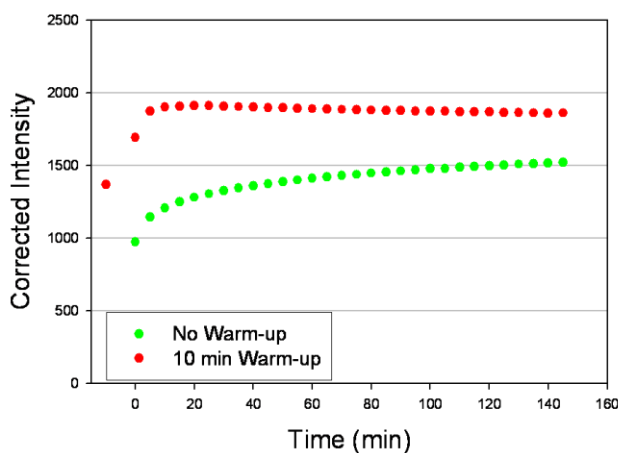


Figure 14. Experiment Three: Sample B Corrected Intensity as a Function of Time, 10 minute Warm-up vs. No Warm-up

2. Voltage

The changes in voltage response were the most significant result of Experiment One. Sample A started at just over 50% of voltage compliance for the first pulse, and by halfway through the experiment the first pulse had reached voltage compliance where it remained for the duration of the experiment, as seen in Figure 15. In addition, transient behavior within the five pulse sequence was observed, although the short term mechanism is not understood. While there does not appear to be a direct link to intensity, it is worth noting that as the pulses climbed to voltage compliance, the intensity dropped.

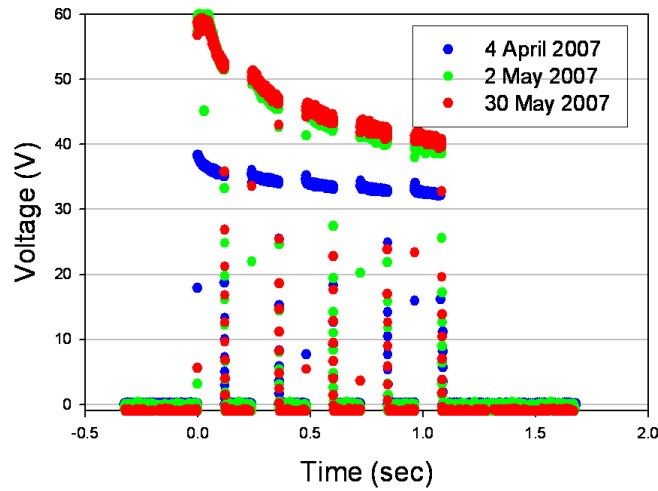


Figure 15. Experiment One: Sample A Voltage as a Function of Time, Three Different Test Dates

Figure 16 shows that Sample B started at 83% of voltage compliance on the leading edge of the first pulse and then by the end of the experiment that leading edge was at voltage compliance. Sample B had the highest intensity of the three samples and took the longest to reach voltage compliance for the full cycle.

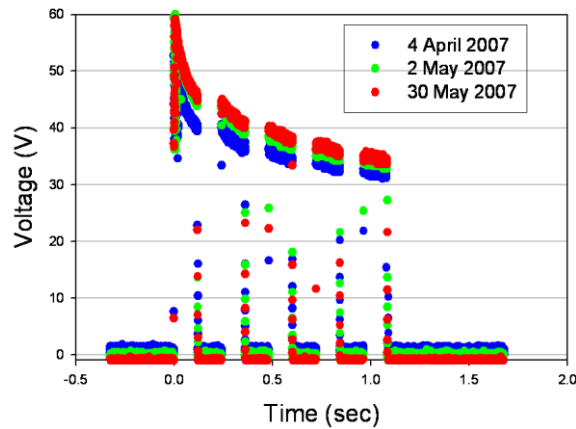


Figure 16. Experiment One: Sample B Voltage as a Function of Time, Three Different Test Dates

Sample C started with the leading edge of the first pulse at compliance and ended with all five pulses at compliance, as shown in Figure 17. This is the type of emitter in the IIFF Patch Generation 3, and the data suggest that the encapsulation method was allowing too much moisture into the device, adding to the degradation of intensity and voltage response. As the sample's voltage response goes to compliance, the current level will drop below its optimum value and the efficiency will decrease.

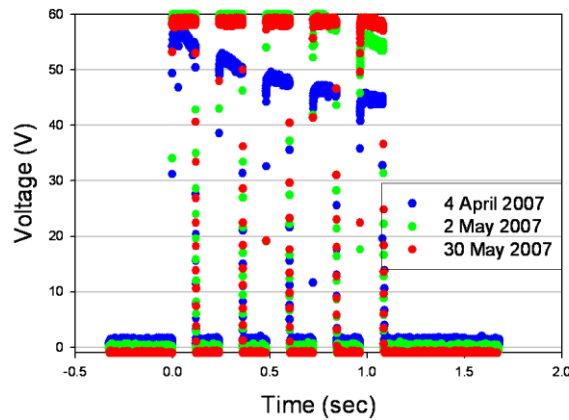


Figure 17. Experiment One: Sample C Voltage as a Function of Time, Three Different Test Dates

The results of Experiment Two were even more interesting in terms of voltage response. Sample A was pulsed over a shorter time interval, and like the intensity, the voltage response was affected. The first pulse started at compliance (where it had ended in the previous experiment) and proceeded to drop to just over 50% of voltage compliance as a result of repeated “short term” activation, as seen in Figure 18. The transient behavior seen in the voltage response from Experiment One and in the initial pulses of this experiment was greatly reduced by the end of Experiment Two.

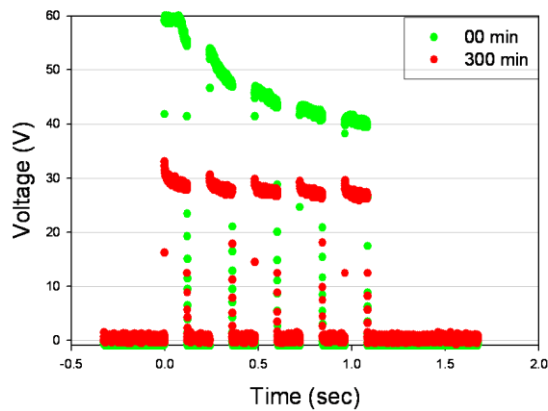


Figure 18. Experiment Two: Sample A Voltage as a Function of Time, Comparing $t=0$ and $t=300$ minutes with Activation Every 5 minutes

The third experiment, with a new B sample, tracked similar changes in voltage response as seen in Experiment Two, between the warmed-up sample and the cold sample, as shown in Figure 19. The sample that was not warmed-up started at voltage compliance and had a large voltage transient behavior during the pulse cycle. The sample that had the ten minute warm-up started at 32% of the compliance voltage and remained steady for all five pulses, with no apparent transient behavior.

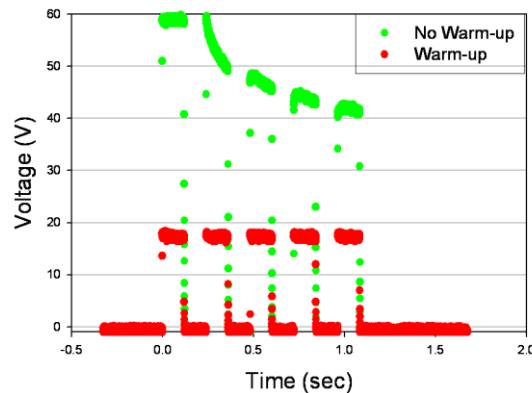


Figure 19. Experiment Three: Sample B Voltage as a Function of Time, Comparing Initial and “Post Warm-up” Behavior for the Initial Pulse

At the conclusion of Experiment Three, the final voltage of the cold sample had dropped so that only the leading edge of its first pulse was at compliance. The warm sample's voltage had increased to roughly 47% of voltage compliance, as seen in Figure 20. The transient behavior of the pulses appeared to be similar for both samples.

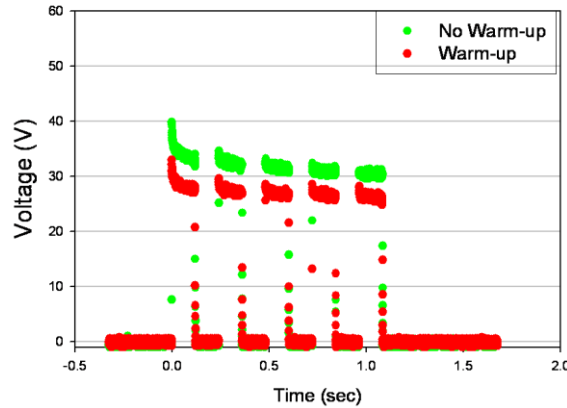


Figure 20. Experiment Three: Sample B Voltage as a Function of Time, Comparing Initial and “Post Warm-up” Behavior for the Final Pulse

B. RED SAMPLES

Three experiments were performed with the red sample D. Experiment Four involved pulsing the device over a short period of time to see if the sample reproduced the yellow sample's intensity increase. The fifth experiment was then to see the differences between cold and warm samples and Experiment Six was an attempt to determine the device “reset” time. “Reset” time was defined to be the time it took the device to go from optimum intensity after a warm-up period, back to the pre-warm-up intensity.

1. Intensity

The fourth experiment did show the rise in intensity during repeated activation as observed in the yellow samples (Figure 21). The red samples experienced a greater fractional change than the yellow samples.

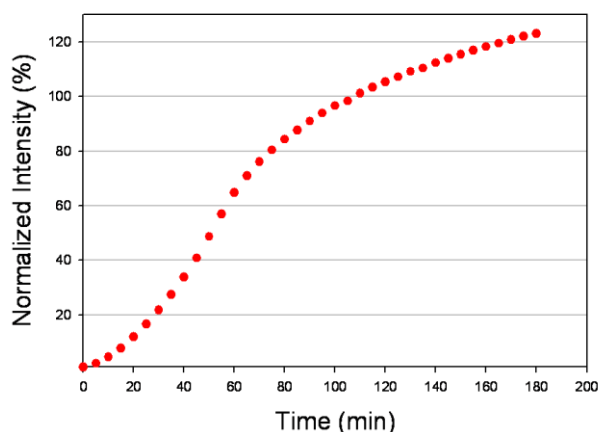


Figure 21. Experiment Four: Sample D Normalized Intensity as a Function of Time, Repeated Activations Every 5 minutes

In Experiment Five the sample had a warm-up period (10 min of steady 3 mA current) prior to pulsing. The fractional change during operation after warm-up was also smaller than that of the yellow sample (Figure 22).

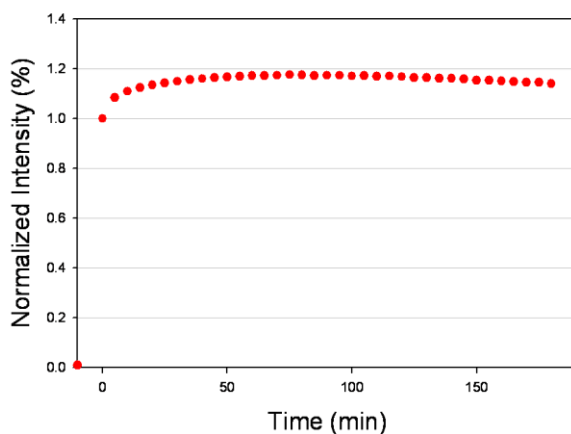


Figure 22. Experiment Five: Sample D Normalized Intensity as a Function of Time, Warmed-up for 10 minutes and Activated Every 5 minutes

The sixth experiment was to determine how long after a device was warmed-up was required for the device to return to its pre-warm-up intensity, or how long before the device reset. The initial time interval used was thirty minutes between activations, for about 210 min, which proved to be too short of a time scale, as shown in Figure 23. The

time interval between activations was changed to arbitrary time periods for 4 days, which led to the discovery that the devices reset, after a 10 min warm-up, in 3.8 days (Figure 24). At the 1.2 day mark, the intensity was 50% of the optimum intensity, and at the 3.8 day point, the intensity was 17% of the optimum intensity.

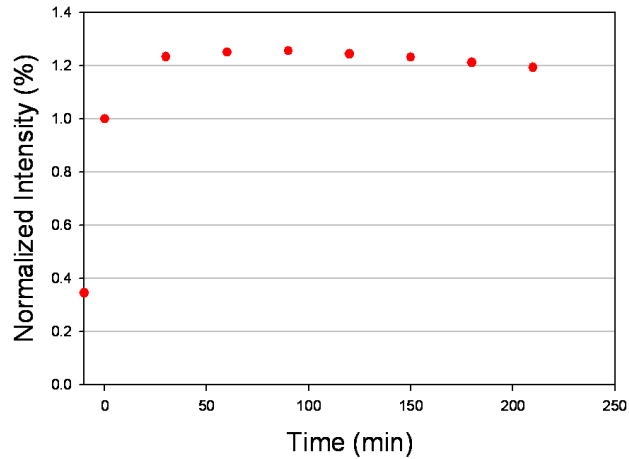


Figure 23. Experiment Six: Sample D Normalized Intensity as a Function of Time, 30 minute Activations following 10 minute Warm-up Period

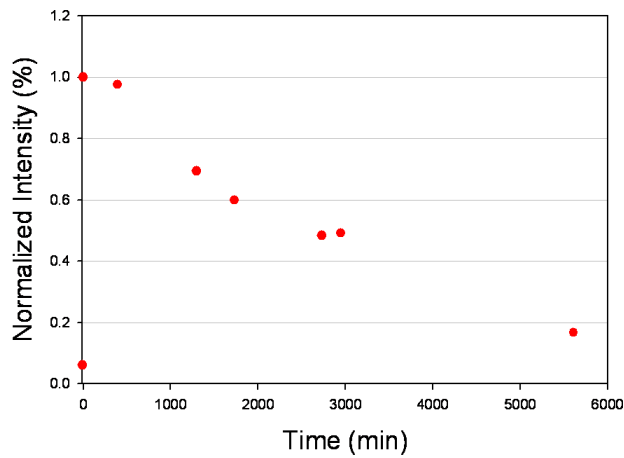


Figure 24. Experiment Six: Sample D Normalized Intensity as a Function of Time, Arbitrary Activations following 10 minute Warm-up Period

The implications of this for the patch are that after turning on the device for 12 hours (one night), even with a warm-up, the intensity will have dropped significantly. A unit going on patrol at night would turn on the IIFF patch, with a warm-up cycle, and have optimum intensity, but 12 hours later, the intensity would have dropped so significantly that the visibility and range of the patch could be detrimentally affected, thus limiting the effectiveness of the patch.

2. Voltage

Experiment Four, which was to establish a baseline of voltage response for the red samples, pulsed the device every 5 minutes for 180 minutes. All five pulses were at voltage compliance initially, and then all five pulses dropped to 83% of voltage compliance (Figure 25). The red devices were brand new and had little on-time in comparison with the yellow samples, which may explain the high voltage response. Unlike the yellow samples, the red sample pulses showed minimal transient behavior during the activation cycle.

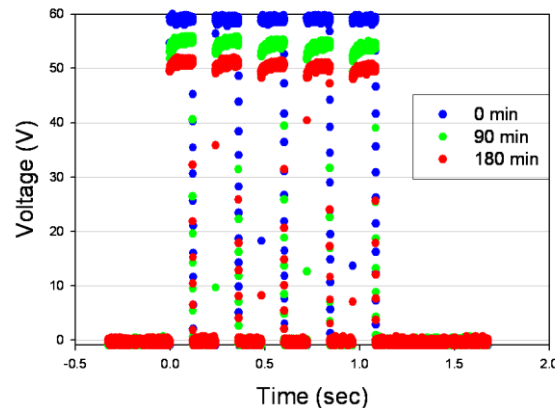


Figure 25. Experiment 4: Sample D Voltage as a Function of Time, Activation Every 5 minutes

The fifth experiment saw the initial pulses at voltage compliance, the pulses after the 10 min warm-up dropping to 37% of voltage compliance and, at the end of the experiment, all pulses at 50% voltage compliance (Figure 26).

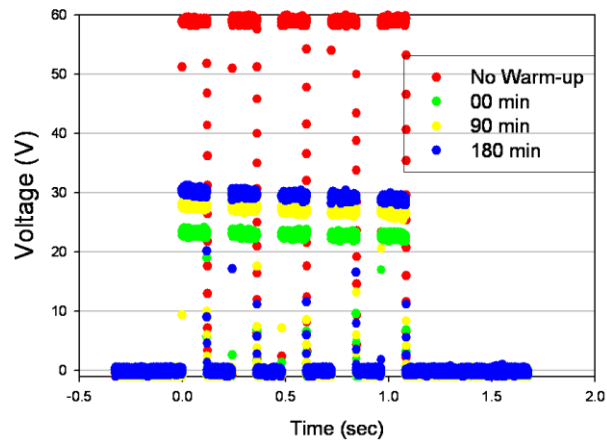


Figure 26. Experiment Five: Sample D Voltage as a Function of Time, No Warm-up vs. Warm-up

The sixth experiment, in attempting to determine the time constant for device reset, saw nothing new in the voltage data for the 30 min intervals (Figure 27). However, the 24 hour time intervals produced some interesting results. Individual pulses developed transient behavior, as seen in Figure 28.

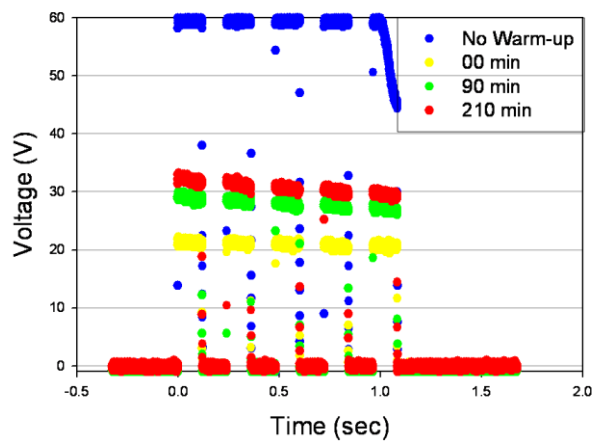


Figure 27. Experiment Six: Sample D Voltage as a Function Time, 30 minute Activations

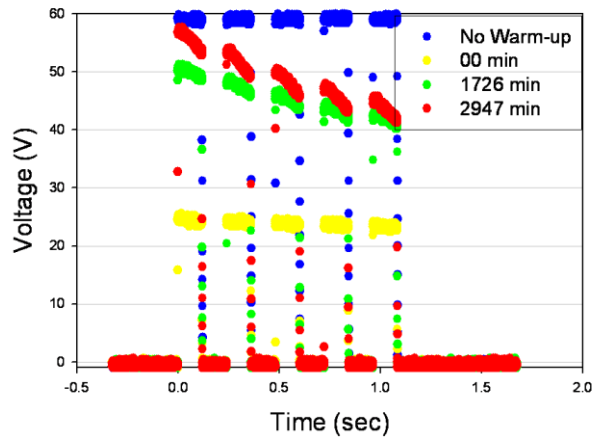


Figure 28. Experiment Six: Sample D Voltage as a Function of Time, 24 hour Activations

C. IIFF PATCH

In order to demonstrate the effect of these behaviors on actual device operation, an experiment on the IIFF patch itself was performed as Experiment Seven. Experiments with the yellow samples had demonstrated that providing some sort of warm-up significantly increased the intensity. The goal of the experiment was to determine the effect of a warm-up on overall brightness of an IIFF patch.

1. Intensity

The patch was activated once, then placed in beacon mode for 5 minutes, and then activated again. The resulting 2184×1472 pixel² images, from the Apogee KX32MED CCD camera, were then cropped to 494×271 pixel² images for intensity analysis. The average intensity was then calculated by Micro CCD 4.01. The patch at initial activation had an intensity of 1851, compared to the intensity of the final activation of 3171. The resulting intensity values showed an increase of 170%, an important consideration in the next design of the IIFF patch. Another design issue that came to light from this experiment was the non-uniformity between the intensity of the left side of the chevron

and the right side of the chevron (Figure 29). This suggests that a chevron may not be the optimum design for the emission area of the patch. The same intensity data are presented in Figures 30 and 31 in 3 dimensions, with intensity values on the z-axis.

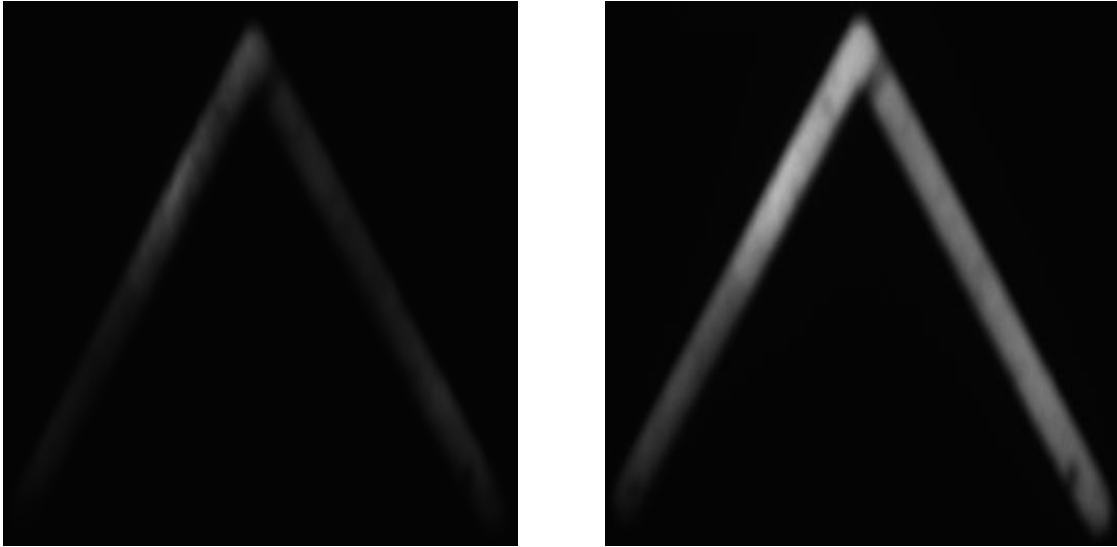


Figure 29. IIFF Patch Pre-Warm-up Intensity (1851) vs. Warm-up Intensity (3171)

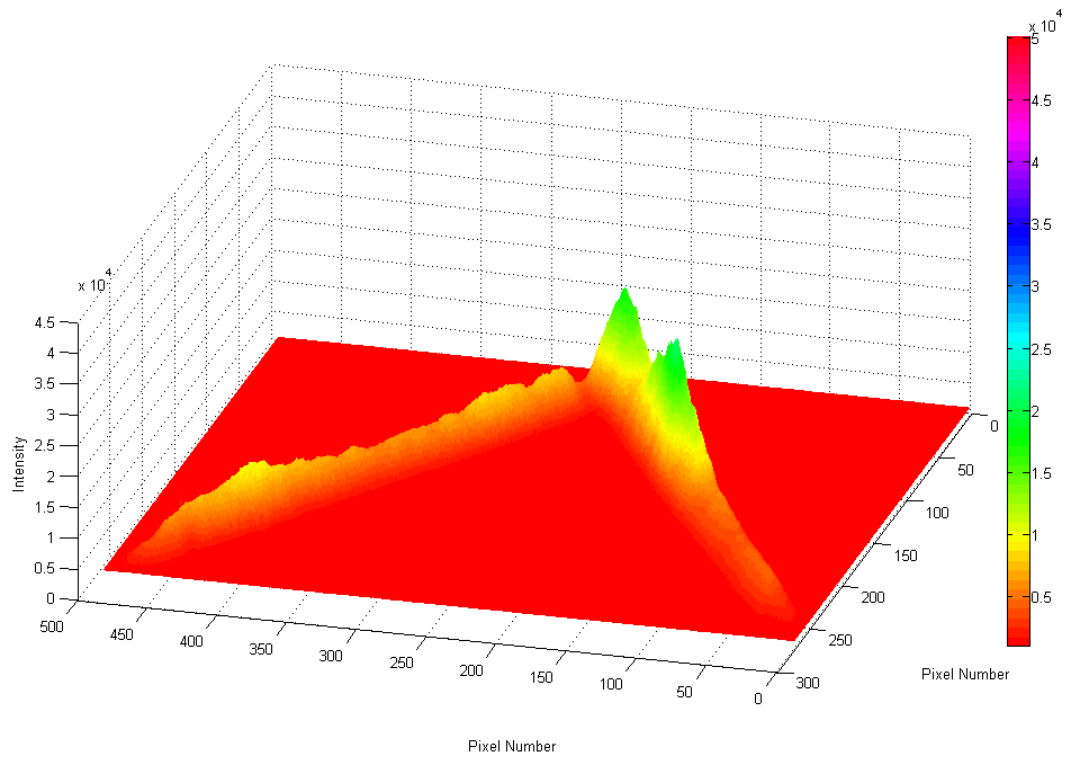


Figure 30. IIFF Patch Generation 3 Experiment Seven Pre-Warm-up

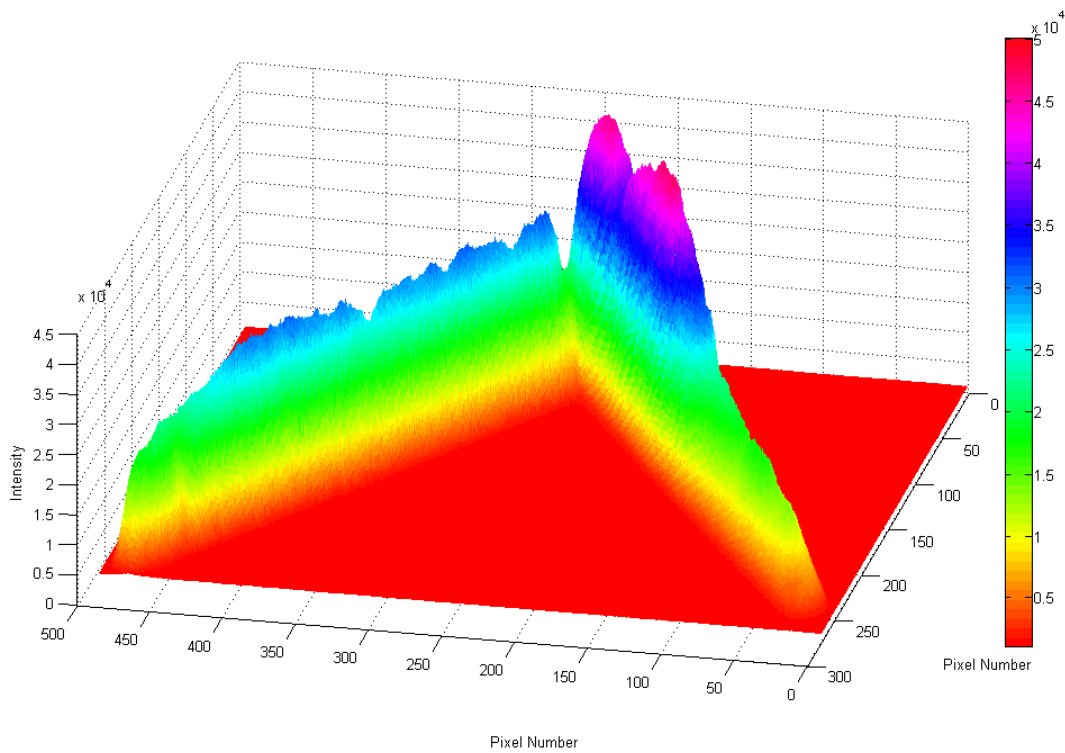


Figure 31. IIFF Patch Generation 3 Experiment Seven Post-Warm-up

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V. CONCLUSION

A. COMPARISON WITH LEC

The LEPs, pulsed over short periods of time, or given a warm-up period, demonstrated similar increases in intensity that had been reported for LECs driven under constant current. The voltage increase seen in the LEPs was also similar to the voltage increase reported in LECs. A possible explanation is that as the dopants clear out of the middle layer, under a constant current as provided during the warm-up period, the luminescent efficiency improves. Another explanation may be that constant activation or steady current may cause the burnout of non-radiative defects, since each time the p-OLED is turned on the current must drive out any moisture that has accumulated. These theories, based on LEC literature and the experimental results presented here, are all hypotheses, but clearly more research needs to be done on the actual physical mechanisms affecting luminescence efficiency in the short time-frame explored in this thesis.

B. IIFF PATCH DESIGN

Regarding the IIFF Patch design, there are changes required in the type of LEP used, and the illumination design of the patch. The data demonstrate that the red LEP has the greatest intensity without requiring the large warm-up period, while the Yellow LEP has the lowest turn-on voltage, even before the warm-up period. This suggests that the Red LEP provides the best design possibility for the current patch, since the intensity is achieved without dramatic impact on voltage requirements, which affects the battery life.

The optimum intensity of both LEPs was achieved by providing a warm-up period of constant current. The design of the IIFF patch should incorporate a means of providing such a warm-up period without excessively draining the battery. This means a redesign of the patch and a review of the replaceable AAA battery. A non-replaceable coin cell battery, which was once considered, may still be an option, or the final decision could be that the battery lifetime of the patch is only supposed to be 1-2 patrols.

Another design correction in the IIFF patch is the chevron pattern. The chevron clearly does not result in uniform illumination, which could be affecting overall intensity of the patch. A possible design that could address this issue is to make a square, the same size as the coupons used in this thesis. The emission is then concentrated in a more compact area and the patch size could be made smaller.

C. FUTURE WORK

More work on emission behavior in a time frame on the order of seconds is needed for LEPs and even LECs. There is no published research on LEP device behavior in the first seconds or minutes of activation. Also, continued research is needed to define the mechanisms for the rise in intensity and voltage of the devices.

In regards to this thesis, current and future research is focusing on combining the red and yellow dyes of the LEPs in order to obtain a device that has the high IR intensity of the red and the low driver voltage requirements of the yellow. Such a device would provide the best of both worlds as seen in experimental results, because it would not require a warm-up period, thus increasing battery lifetime, and would allow for minimal design changes in the IIFF patch, compared to a complete driver circuit overhaul.

Another area of future research is that of increasing the intensity in the near-IR wavelength range. By increasing the intensity in the near-IR, the efficiency of the device would be improved, increasing the maximum range of the device. This increase in near-IR intensity may be possible using quantum dots or improved doped red dyes. Quantum dots could be used as an additional active filter layer to the p-OLED, while the improved dyes would simply affect the LEPs.

This thesis has demonstrated the need for understanding the short term transient behavior of LEP devices. The information gained from the LEP devices can be used for improved IIFF patches. I believe that these transient behaviors can be controlled and or utilized to optimize emissions for the patch in a desired time frame. Such control or utilization will allow these new materials to be used for this unique application in suppressing military fratricide.

APPENDIX. KEITHLEY SOURCE METER PROGRAMMING SPCI CODE (SCPI.TXT)

```
:*RST
:TRAC:CLE
:TRAC:POIN 5
:*SRE 1
:TRIG:COUN 5
:SYST:AZER:STAT OFF
:SOUR:FUNC CURR
:SENSE:FUNC:CONC OFF
:SENSE:FUNC "VOLT"
:SENSE:VOLT:NPLC 0.08
:SENS:VOLT:RANG 20
:SENS:VOLT:PROT:LEV 60
:FORM:ELEM VOLT
:SOUR:CURR 0.003
:TRIG:DEL 0.11978
:SOUR:DEL 0.118432
:TRAC:FEED:CONT NEXT
:SOUR:CLE:AUTO ON
:INIT
:TRAC:DATA?
```

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*RST;
*CLS;
*SRE 0;
:STAT:MEAS:ENAB 0
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